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High-Speed and High-Responsivity InP-Based Uni-Traveling-Carrier Photodiodes

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ABSTRACT In this paper, top-illuminated InP-based uni-traveling-carrier photodiodes (UTC-PDs) with dipole-doped structure which achieve both high speed and high responsivity simultaneously have been reported. With optimization of device size and layer structure, dipole-doped UTC-PDs have demonstrated a measured optical-to-electrical 3-dB bandwidth of over 40 GHz and a maximum responsivity of 0.6 A/W at optical input power of 100 mW. By using a semi-analytical equivalent circuit model, the 3-dB bandwidth was predicted to be 103 GHz. This high 3-dB bandwidth and responsivity yield a high figure-of-merit value of 61.8 A/W·GHz.

INDEX TERMS Dipole-doped structure, high speed, high responsivity, uni-traveling-carrier photodiode (UTC-PD), 3-dB bandwidth.

I. INTRODUCTION

Photodiodes (PDs) with high photocurrent, high responsivity and large 3-dB bandwidth are of great importance for the development of future large-capacity fiber-optic communication systems and ultrafast measurement systems and are attracting intensive research interests due to their broad applications in high-performance microwave or millimeter-wave photonic systems [1]–[3]. Several types of UTC PDs [3]–[11] designed to achieve high responsivity and large bandwidth have been reported.

One of the key structure designs to optimize the performance of UTC-PD is to suppress the current blocking at the interface between the absorption and collection layer. Usually, InGaAsP compositional graded quaternary structures are employed between the small-bandgap light absorber and wide-bandgap carrier collector to reduce the energy barrier, facilitate carriers traveling and relieve the carrier accumulation. However, the presence of compositional graded InGaAsP layers at InGaAs/InP interface could result in the complexity and difficulty in the material growth and subsequent device fabrication [3]. In our devices, an InGaAs/InP dipole-doped structure in combination with a setback layer has been used.

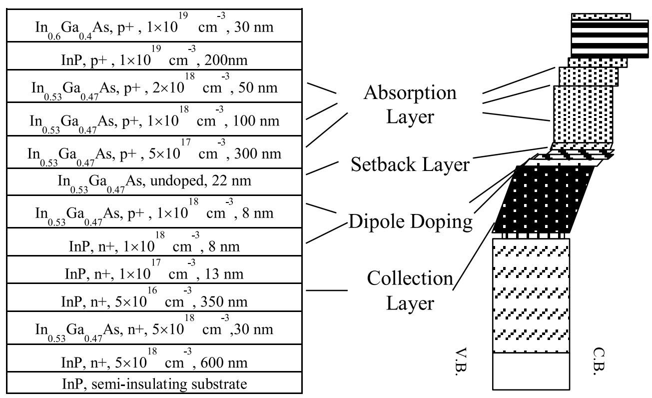

FIGURE 1. Epi-layer structure and schematic energy band diagram of dipole-doped UTC-PD.

The dipole-doped UTC-PDs have demonstrated high photocurrent of 160 mA as well as large 3-dB bandwidth (f_{3dB}) of 62.5 GHz reported in our previous work [3]. The use of dipole-doped interface may ease the material growth and device fabrication without compromising the device performance.

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Another design aspect to pursuit the ultimate high frequency 3-dB response is that the device is typically designed with a thin absorption and collection layer and a smaller active area than that for p-i-n structures to reduce the carrier transit time and junction capacitance [1]. However, the responsivity is normally compromised in such devices. In order to maintain a reasonable responsivity, the device with small active area requires a more complicated device structure such as backside illumination or waveguide design, which would result in high costs for design, fabrication and assembly. As an example, when the device active area of UTC-PD is downscaled to 5 μm^2, ultra-high speed performance (f_{3dB} of 310 GHz) has been achieved at the 1.55 μm wavelength operation [5]. However, such a high f_{3dB} can only occur in a very small range of dc reverse bias condition (0.5 to 0.7 V), and under a small load resistance (12.5 Ω) for sustaining a high RC-limited bandwidth [4], [5]. This small load resistance would reduce the output power as compared to that of PD under a standard 50 Ω load and the same operation current [4]. Further more, a thinner absorption layer would largely affect the responsivity performance of device with a limited responsivity as low as 0.07 A/W [4], [5]. Thus, optimization of device layer structure design which could enable UTC-PD achieve high-speed performance without compromising the responsivity is still of research interest.

In this paper, with optimized design of device dimension, layer thickness and structure, top-illuminated UTC-PDs with dipole-doped structure have demonstrated a measured O-E 3-dB bandwidth of over 40 GHz and responsivity result of 0.6 A/W at 1.55 μm wavelength.

II. DEVICE STRUCTURE AND THEORY ANALYSIS

A. DEVICE STRUCTURE

Fig. 1 shows the epi-layer structure and band diagram of the dipole-doped UTC-PD. The active region of device consists of a 450 nm InGaAs absorption layer graded in three steps, to form a quasi-neutral electric field to aid carrier transport, and a 370 nm InP carrier collection layer. The transitional dipole-doped structure consists of an 8-nm-thick 1×10^{18} cm^{-3} p-doped InGaAs layer and an 8-nm-thick 1×10^{18} cm^{-3} n-doped InP layer, and a 22 nm setback layer. The dipole-doped structure was grown by molecular beam epitaxy (MBE). The effectiveness of using dipole-doped structure to reduce the current blocking effect has been validated by simulating the energy band profile of UTC-PD and reported in our early publication [3].

By using conventional photolithography, wet chemical etching and benzocyclobutene (BCB) passivation, double-mesa structure UTC-PDs have been fabricated with different dimensions aiming for high 3-dB bandwidth and high responsivity. DC and RF performance of UTC-PDs with different dimensions were characterized at a light wavelength of 1.55 μm. The detailed fabrication process and measurement setup were presented in reference [3]. Due to the limitation of the RF system, maximum frequency of RF measurement is limited at 40 GHz.

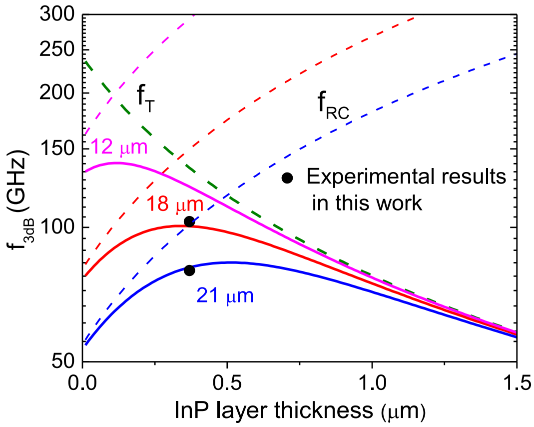

FIGURE 2. Prediction of O-E 3-dB bandwidth considering both the carrier-transit-time limited bandwidth and RC limited bandwidth.

Top-illuminated configuration is employed to ease the device measurement and packaging. However, in our previous design in reference [3], the highly doped $In_{0.6}Ga_{0.4}As$ cap layer would absorb substantial amount of light and result in a significant reduction of the light power penetrate to and absorbed by the $In_{0.53}Ga_{0.47}As$ absorption layer. In order to improve the light absorption in $In0.53Ga_{0.47}As$ absorption layer and improve the device responsivity, the highly doped $In_{0.6}Ga_{0.4}As$ cap layer has been selectively removed by using the P-type electrode as the etch mask. A PECVD Si_3N_4 anti-reflection coating has also been included into the devices. The thickness of the Si_3N_4 is optimized to be 150 nm, which reduces the reflectivity from around 30% to less than 10% at wavelength of 1.55 μm. Furthermore, the BCB at the top window region is removed to avoid any potential absorption. By incorporating these structure optimizations, an improvement in responsivity as compared to previous results in reference [3] could be expected.

B. DESIGN CONSIDERATIONS FOR 3-dB BANDWIDTH OF UTC-PDS

The speed of a PD is mainly limited by two factors: the carrier transit time and the RC delay time. And the overall O-E 3-dB bandwidth can be predicted by:

$$\frac{1}{f_{3dB}^2} = \frac{1}{f_T^2} + \frac{1}{f_{RC}^2} \tag{1}$$

The carrier-transit-time limited bandwidth of UTC-PD can be estimated based on:

$$f_T = \frac{0.55 v_e}{d} \tag{2}$$

TABLE 1. Comparison with UTC-type PDs from other literatures.

Type	Illumination	Size	Max Bandwidth (GHz)	Max Responsivity (A/W)	FOM (A/W·GHz)	Reference
NBUTC-PD	BI	12 μm^2 (Area)	325	0.015	4.875	[4]
UTC-PD	BI	5 μm^2 (Area)	310	0.07	21.7	[5]
MUTC-PD	BI	14 μm (Diameter)	65	0.45	29.25	[6]
RF-UTC-PD	EI	128 μm^2 (Area)	50	1	50	[7]
NBUTC-PD	WG	320 μm^2 (Area)	40	1.14	45.6	[8]
MUTC-PD	BI	25 μm (Diameter)	26	1.14	29.64	[9]
MUTC-PD	BI	28 μm (Diameter)	23	0.82	18.86	[10]
Dipole-doped UTC-PD	**TI**	**18 μm (Diameter)**	**103**	**0.6**	**61.8**	**This work**

BI=Backside Illuminated; EI=Edge Illuminated; WG=Waveguide; TI=Top Illuminated.

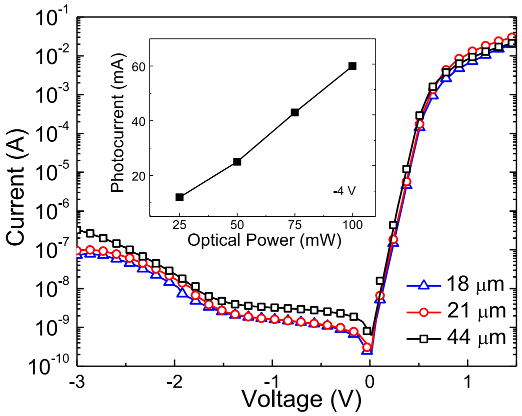

FIGURE 3. DC I-V results of dipole-doped UTC-PD with different diameters. Inset: max responsivity of 0.6A/W measured at 100 mW optical input.

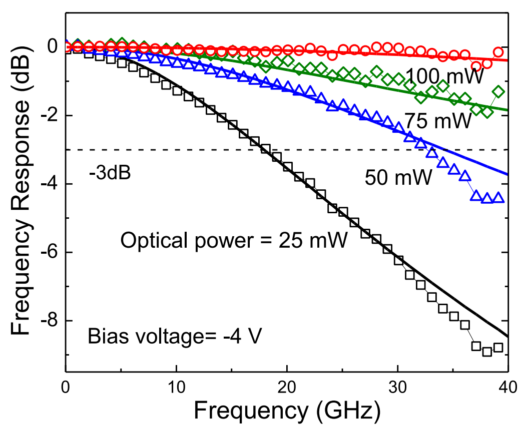

FIGURE 4. Measurement (symbols) and modeling (solid lines) results of a 18-μm-diameter UTC-PD at various optical power conditions at -4 V.

where v_e is the average drift velocity of electron and d is the total drift distance of electron through the depletion layers. Here, we assume that the active region of UTC-PD is completely depleted, which is valid for the UTC-PDs at high reverse bias (> 2 V for our case). For the UTC-PDs using InP and InGaAs, an average drift velocity of 2×10^7 cm/s for electrons drift through the depletion layer can be expected.

As to the RC-limited bandwidth, it can be calculated by:

$$f_{RC} = \frac{1}{2\pi R_L C_T} \tag{3}$$

where R_L is load resistance of 50 Ω in our work. C_T, the total capacitance through the depletion layer, can be determined by:

$$C_T = \frac{\varepsilon_0 \varepsilon_{req} A}{d} \tag{4}$$

where A is the area of UTC-PD's active part, ε_0 is the dielectric constant of vacuum, ε_{req} is the relative equivalent dielectric constant of the total depletion layer. For the junction capacitor of UTC-PD, which is made using different materials including InGaAs and InP with dielectric constant values of ε_{r1} and ε_{r2} and thickness d_1 and $d_2 (d_1+d_2=d)$,

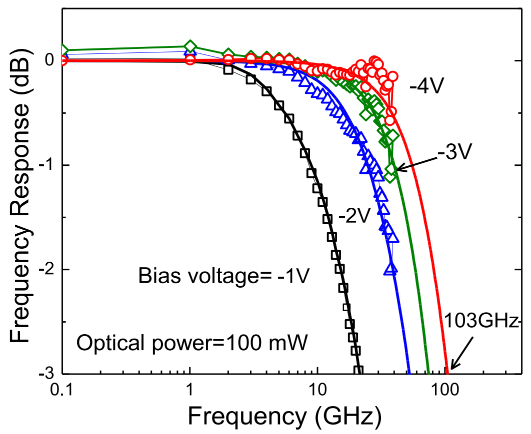

FIGURE 5. Measurement (symbols) and modeling (solid lines) results of a 18-μm-diameter diameter UTC-PD at various dc bias conditions under 100 mW optical input.

the equivalent dielectric constant ε_{req} can be expressed as:

$$\epsilon_{req} = \frac{(d_1 + d_2)\varepsilon_{r1}\varepsilon_{r2}}{d_1\varepsilon_{r2} + d_2\varepsilon_{r1}} \tag{5}$$

Fig. 2 shows the theoretical f_{3dB} (solid lines) for UTC-PD with diameter of 12 μm, 18 μm, and 21 μm based on the structure given in Fig. 1. It can be seen that, for different junction areas (diameters), proper optimization of the thickness for InP layer is needed to achieve a maximum f_{3dB}. For example, compared to the device with a diameter of 12 μm, a thicker InP layer is required for the UTC-PD with a diameter of 18 μm to achieve the maximum bandwidth. In this work, according to the calculation, the total thickness of InP layer is set to be around 0.371 um, which is larger than those reported in the earlier publications [3], [8], and [11]. This is optimized for the top-illuminated UTC-PD with 18-μm diameter, while the performance for other device sizes is compromised.

III. RESULTS AND DISCUSSION

DC measurement has been conducted on dipole-doped UTC-PDs for devices with different diameters. Fig. 3 shows the typical current-voltage (I-V) characteristics measured in the range from -3 V to 1.5 V voltages. The 18-μm-diameter UTC-PD demonstrates a dark current of 7×10^{-8} A at -3 V suggesting the effective Si_3N_4/BCB surface passivation is important for device to achieve high photocurrent (power) performance under high reverse bias. The RF performances of the devices were characterized using Agilent Light Component Analyzer (LCA) N4373D at wavelength of 1.55 μm under various optical input powers (up to 100 mW) and DC bias voltages. An Erbium Doped Fibre Amplifier (EDFA) is used to achieve high optical powers. The maximum frequency is set to 40 GHz due to the system limitation.

For the device biased at -4 V, as shown in the inset of Fig. 3, the photocurrent of 60 mA is obtained at the optical input of 100 mW, which gives the best result of responsivity of 0.6 A/W. Fig. 4 and Fig. 5 show the measurement and modeling frequency response results of an 18-μm-diameter UTC-PD under different conditions. Fig. 4 shows the results of an 18-μm-diameter UTC-PD GHz biased at -4 V. Increase in input optical power results in a drastic increase in devices bandwidth, which is similar to the earlier reports for UTC-PDs by other research teams [8]. For the measurements at high optical power, the 3-dB bandwidth is far beyond 40 GHz. An accurate semi-analytical equivalent circuit model based on the actual device structure and physics of dipole-doped UTC-PD is developed for a better prediction of device bandwidth [12]. The modeling results are plotted as the solid lines in Fig. 4 and Fig. 5, which agree well with measurement results in symbols up to 40 GHz for different optical powers and different bias conditions. The developed model can be used to provide more accurate prediction of the 3-dB bandwidth for the devices with f_{3dB} larger than 40 GHz. The influence of bias voltage on f_{3dB} for an 18-μm-diameter UTC-PD is shown in Fig. 5. A drastic increase in f_{3dB} can be seen when the reverse bias voltage is increased from 1 V to 2 V. This could be attributed to the widening of the depletion region as carrier collection layer may not be fully depleted at the reverse bias voltages below 2 V. The device shows a modeled 3-dB bandwidth of 103 GHz at -4 V. This result shows good agreement with theoretical prediction.

A comparison between our work and UTC-type PDs in other literature is listed in Table 1. So far, most UTC-PDs with large bandwidth or high responsivity were reported on the devices using backside illumination or other complicated designs. It can be seen from Table 1, the ultra-high 3-dB bandwidth of 325 GHz was obtained from a backside-illuminated 12-μm^{2}near-ballistic UTC-PD (NBUTC-PD) by scaling down the area with the sacrificial of the responsivity (0.015 A/W) [4]. The record FOM (product of bandwidth and responsivity) of 50 A/W·GHz was obtained from a polarization-independent edge-illuminated refracting-facet uni-traveling-carrier photodiode (RF-UTC-PD) by use of refracting facet structure [7]. For NBUTC-PD incorporated with evanescently coupled optical waveguide in [8] and backside-illuminated modified UTC-PD (MUTC-PD) in [9], although the relatively high responsivity (both 1.14 A/W) has been achieved with incorporating a waveguide (NBUTC-PD) or thick absorption layer design (MUTC-PD), the bandwidth of the device is compromised. In our work, for the top-illuminated dipole-doped UTC-PD, the 3-dB bandwidth of 103 GHz and the responsivity of 0.6 A/W yield a high FOM of 61.8 A/W·GHz among the reported UTC-type PDs.

IV. CONCLUSION

In this paper, a top-illuminated high-speed and high-responsivity InP-based UTC-PD with dipole-doped structure is presented. By optimizing the device size and layer structure design, a large O-E 3-dB bandwidth of over 40 GHz, which can be predicted to be 103 GHz by using a semi-analytical modeling method, and a responsivity of 0.6 A/W at optical input power of 100 mW are demonstrated. A high FOM value of 61.8 A/W·GHz can be achieved.

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